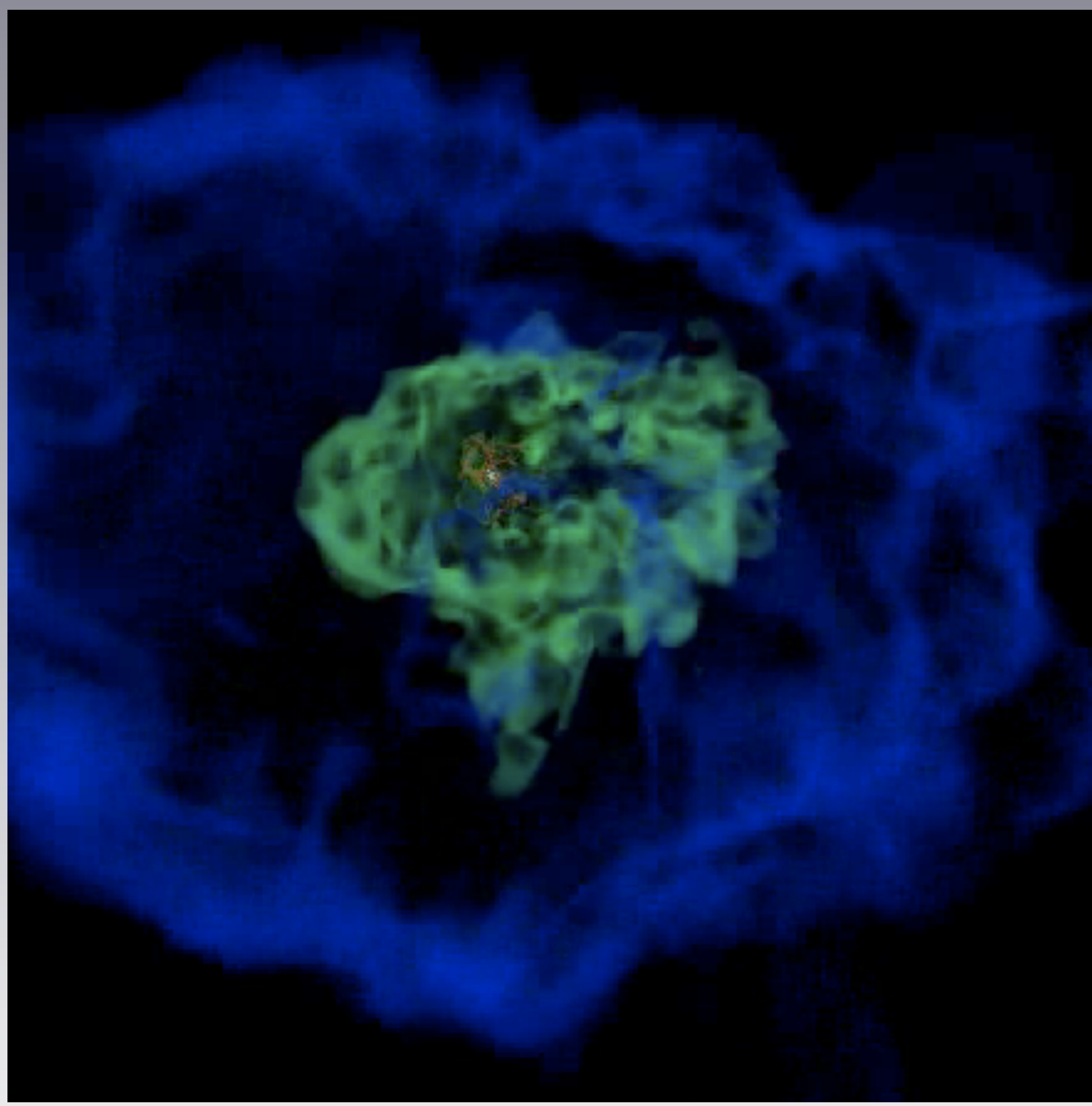
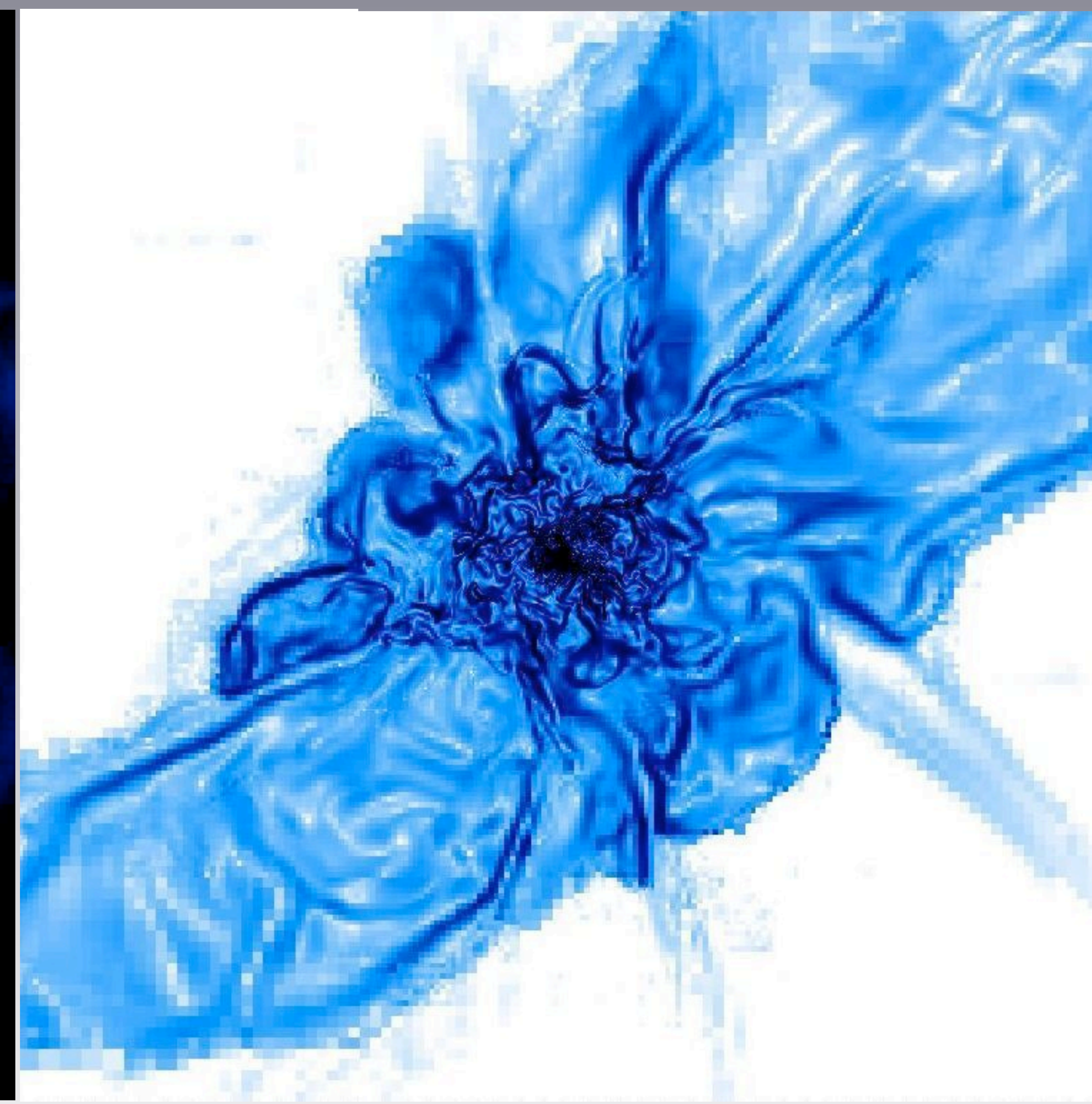
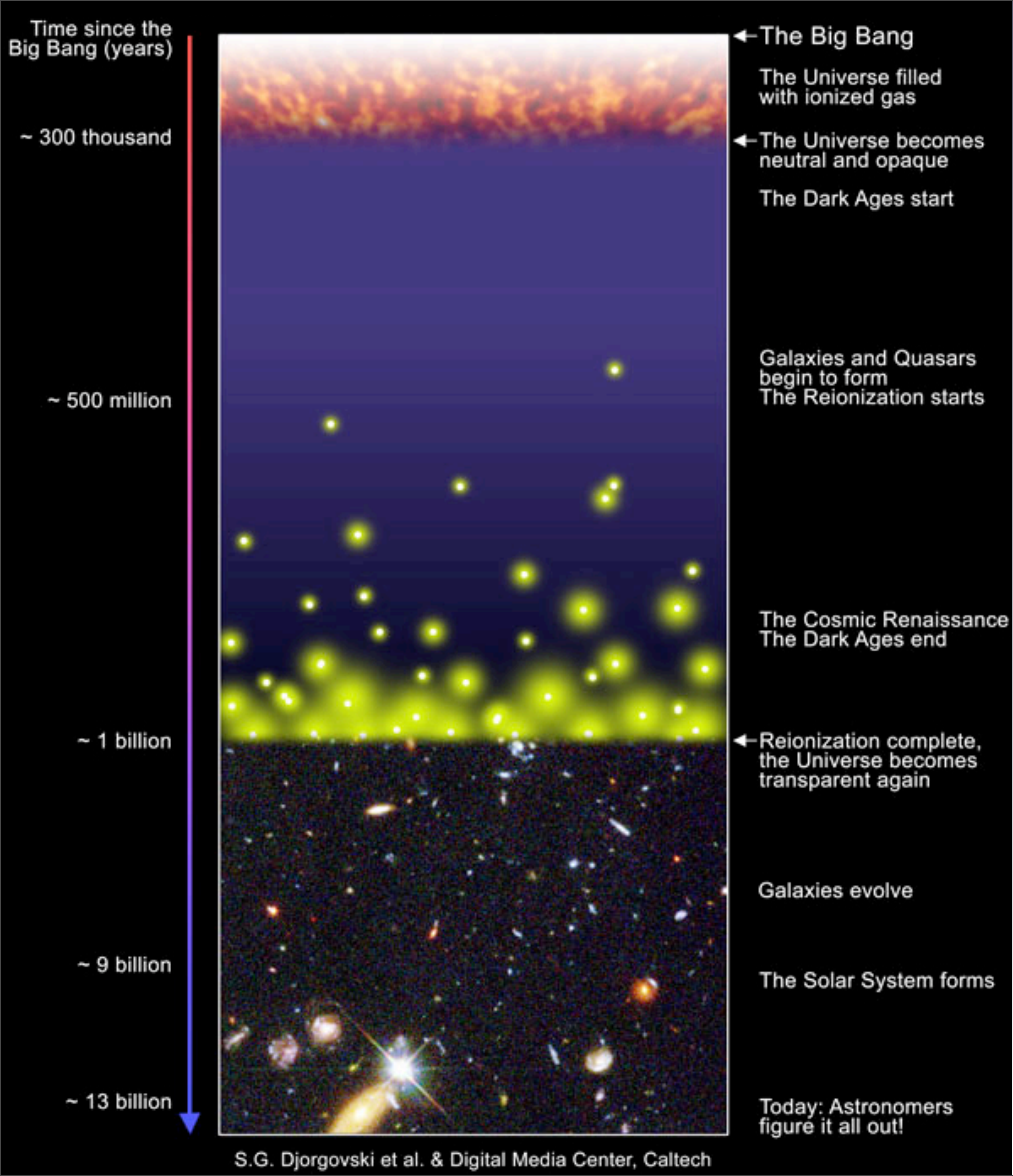
Turbulent Gravitational Collapses in Protogalaxies

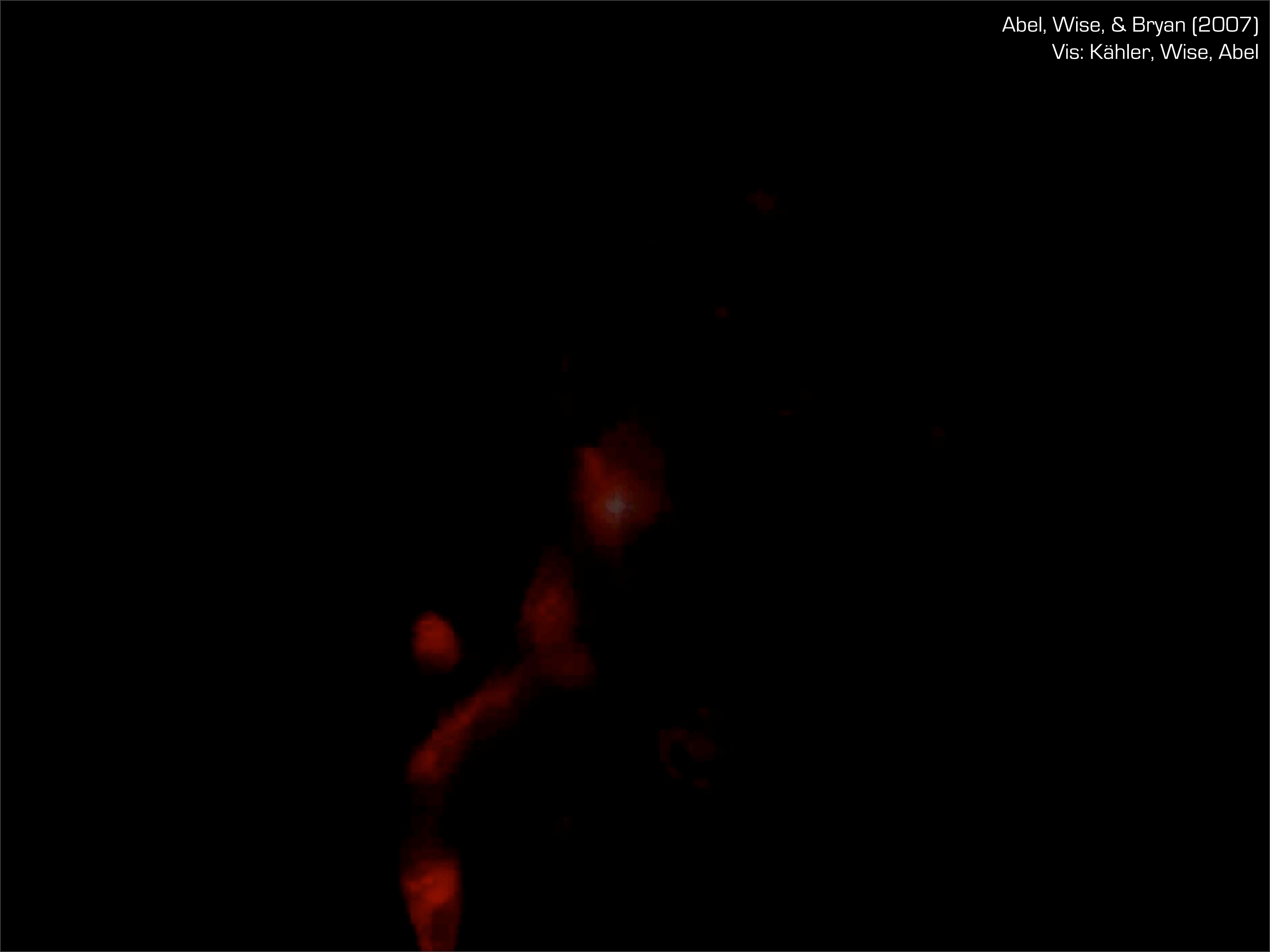



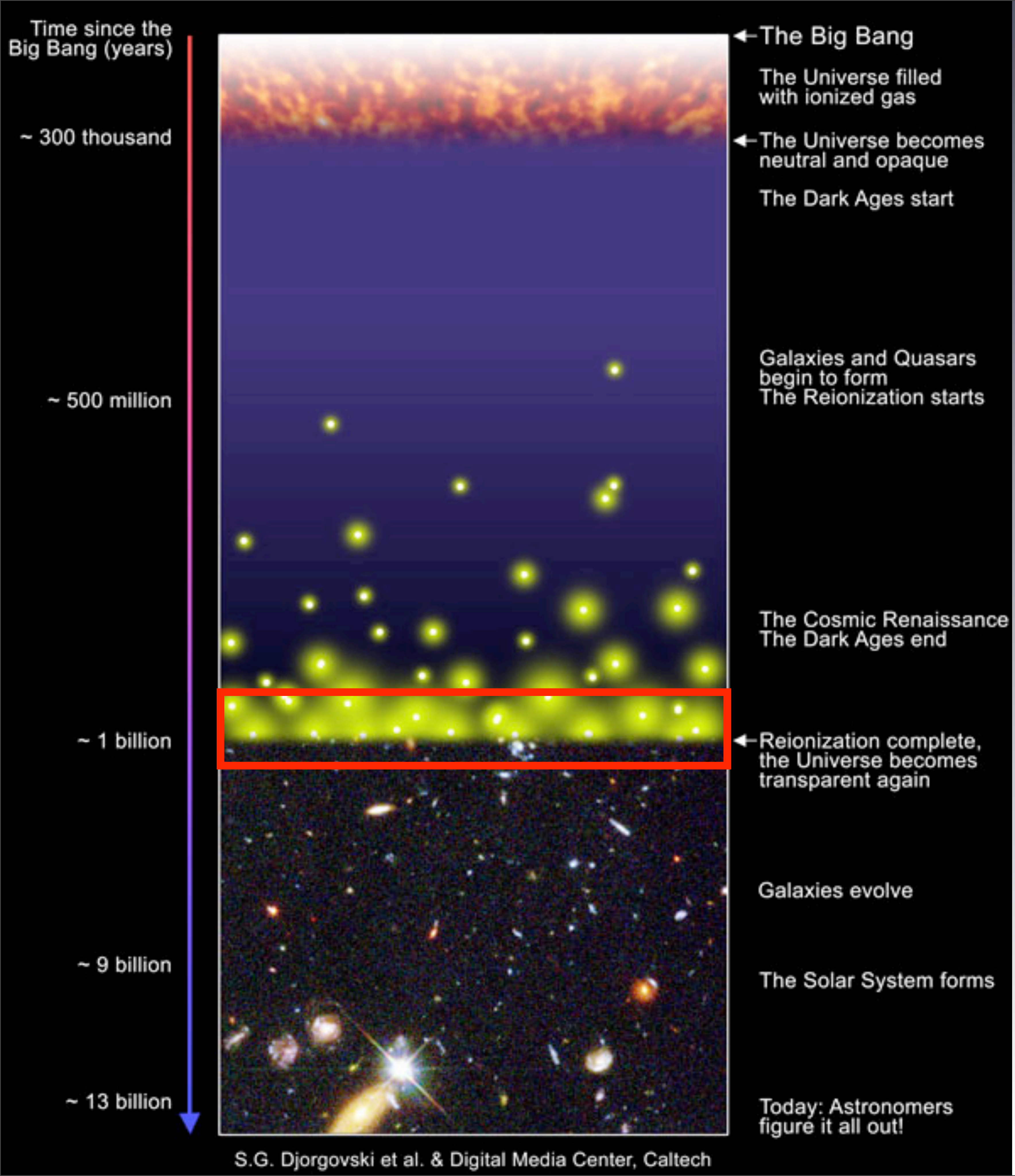
John Wise (NASA / GSFC)

Tom Abel, Matt Turk (KIPAC / Stanford)


Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

Motivation


Abel, Wise, & Bryan (2007)
Vis: Kähler, Wise, Abel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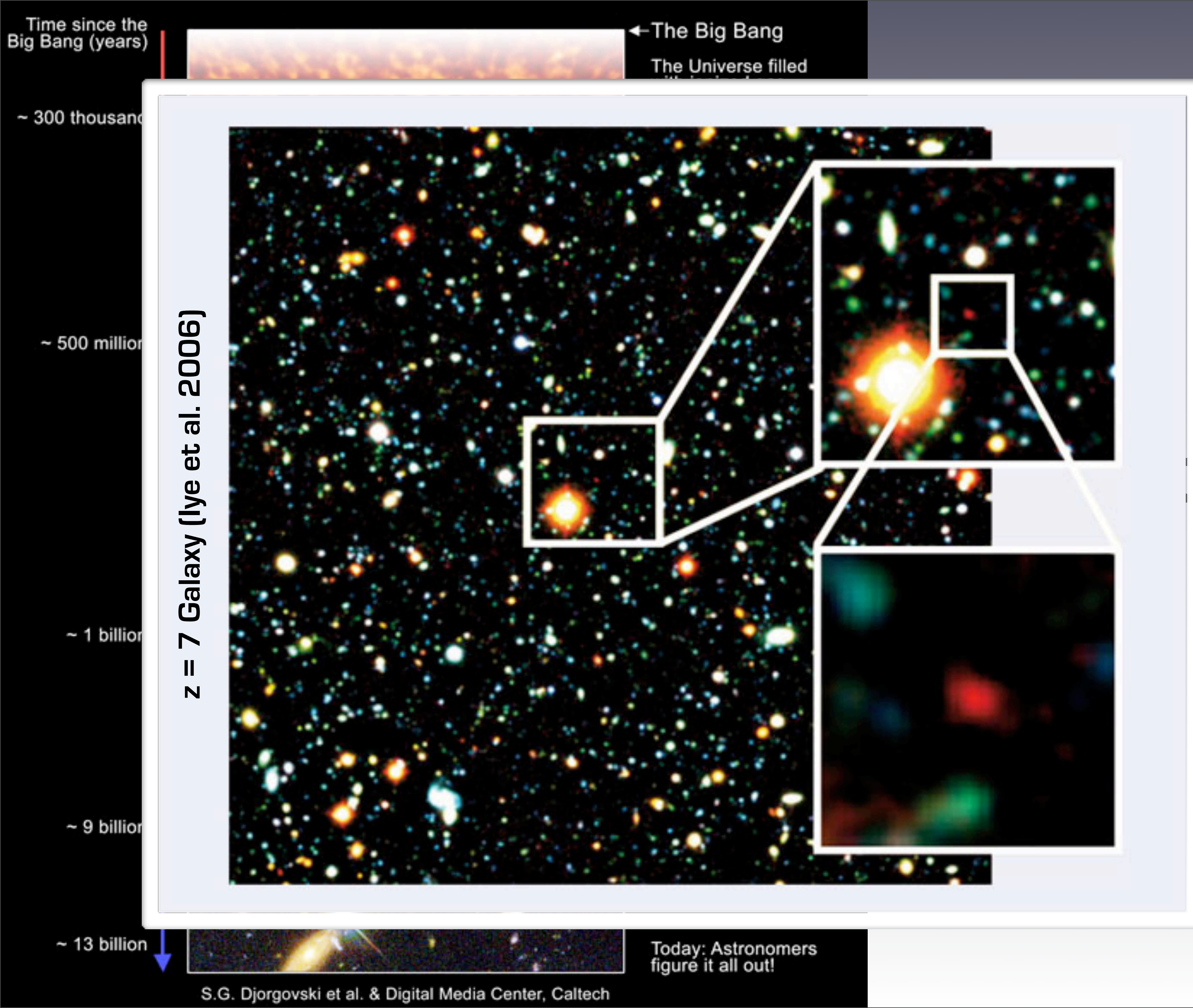
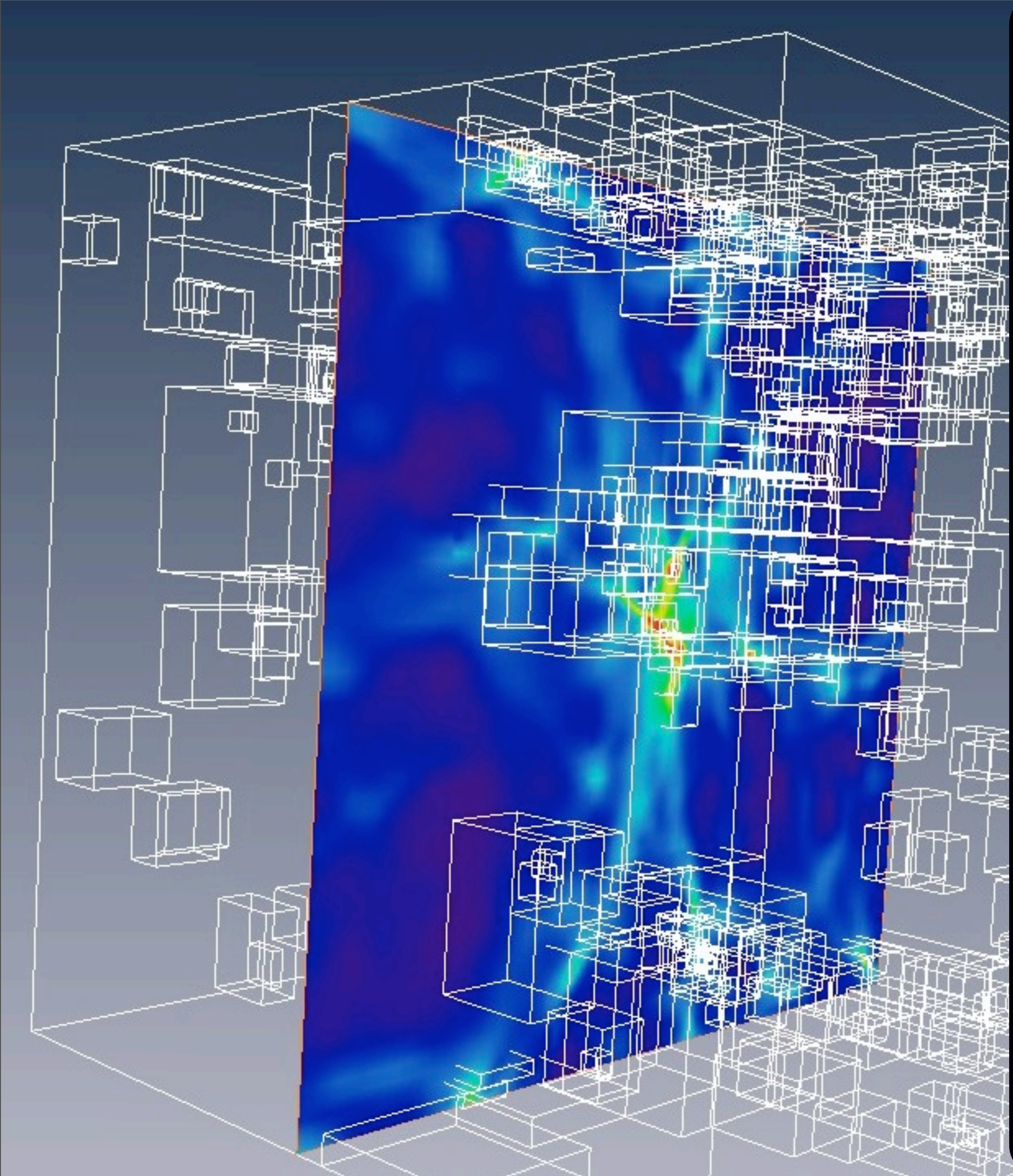


z = 7 Galaxy (Iye et al. 2006)

ion

Enzo



Versatile AMR Code

Bryan & Norman (1997, 1999); O'Shea (2005)

Physics:

- Gravity
- Hydrodynamics
- Non-equilibrium chemistry — Abel et al. (1997)
- Radiation transport — Abel & Wandelt (2002)
- MHD

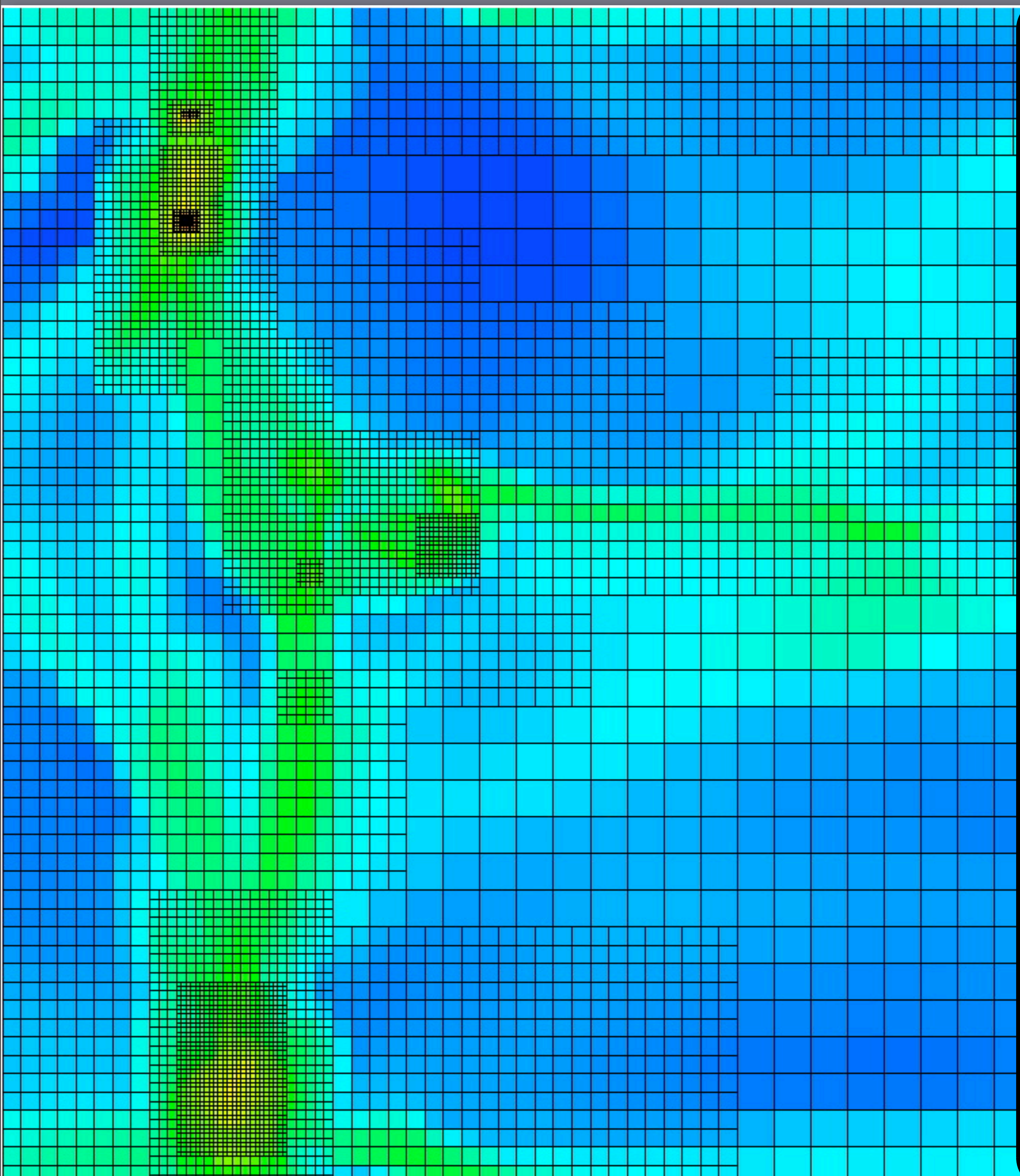
Refinement:

- Baryon overdensity
- Dark matter overdensity
- Jeans length by 16 cells — Truelove et al. (1997)

Stable to 41 levels
(10^{14} dynamical range)

Wise, Turk, & Abel (2008)

Enzo



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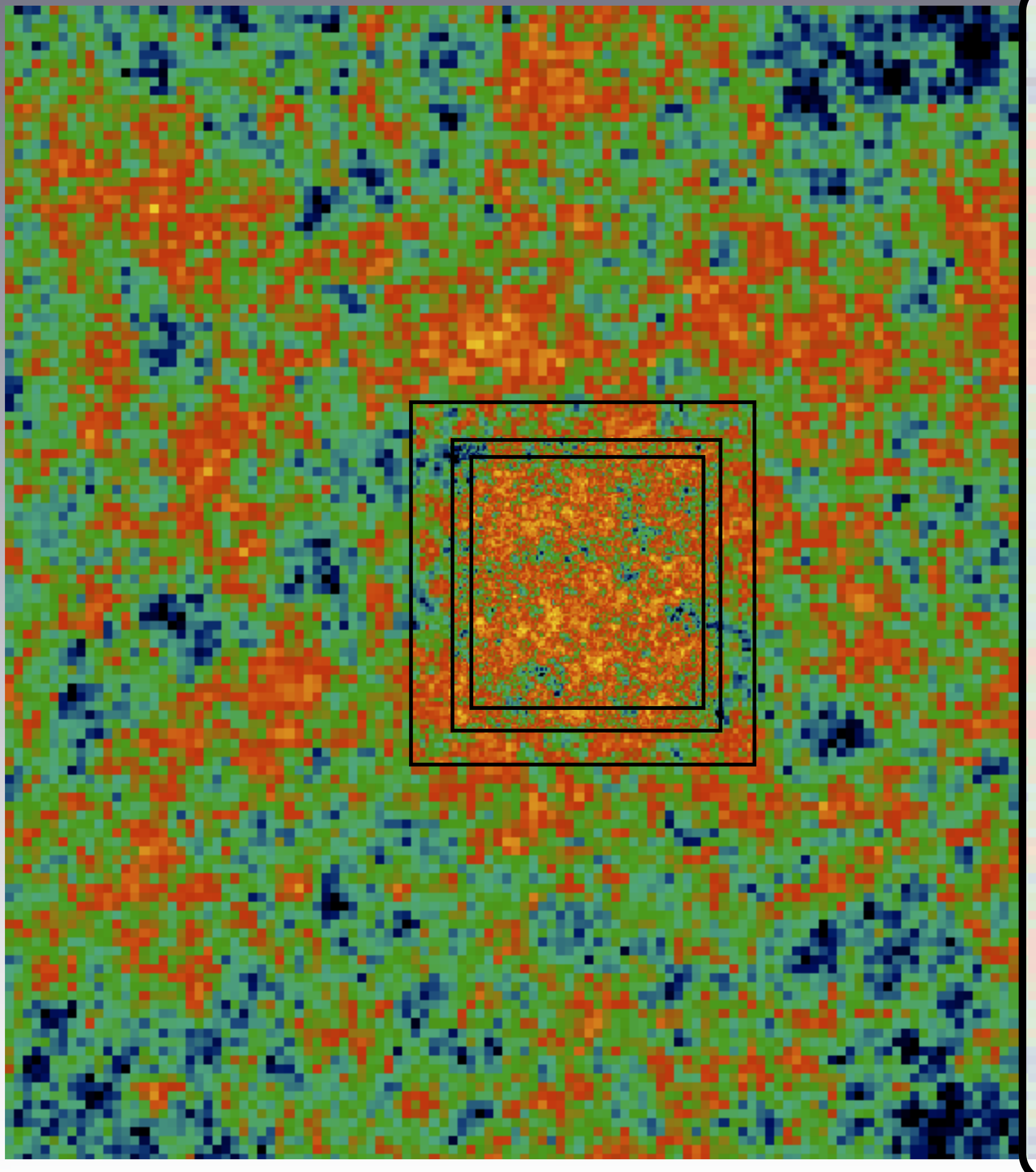
Simulation Setup



- Two random phases:
  - Simulation "A" and "B"
- Atomic H and He cooling
- Focus on the hydrodynamics of the collapse of a 10^4 K halo
- Neglect:
  - H_2 cooling
  - Stellar formation and feedback

	Simulation A	Simulation B
Initial Redshift	130	120
Comoving Box Size	1.0 Mpc	1.5 Mpc
DM Mass Resolution	30 $M_\odot$	100 $M_\odot$
Maximum # of Unique Cells	1.2×10^8 (494^3)	6.5×10^7 (420^3)

Why study this?

- Initial conditions are well-established.
- Poses an excellent numerical experiment for a turbulent collapse.
- Possibly applicable to both galaxy formation and molecular clouds.
- Control model for calculations with feedback.

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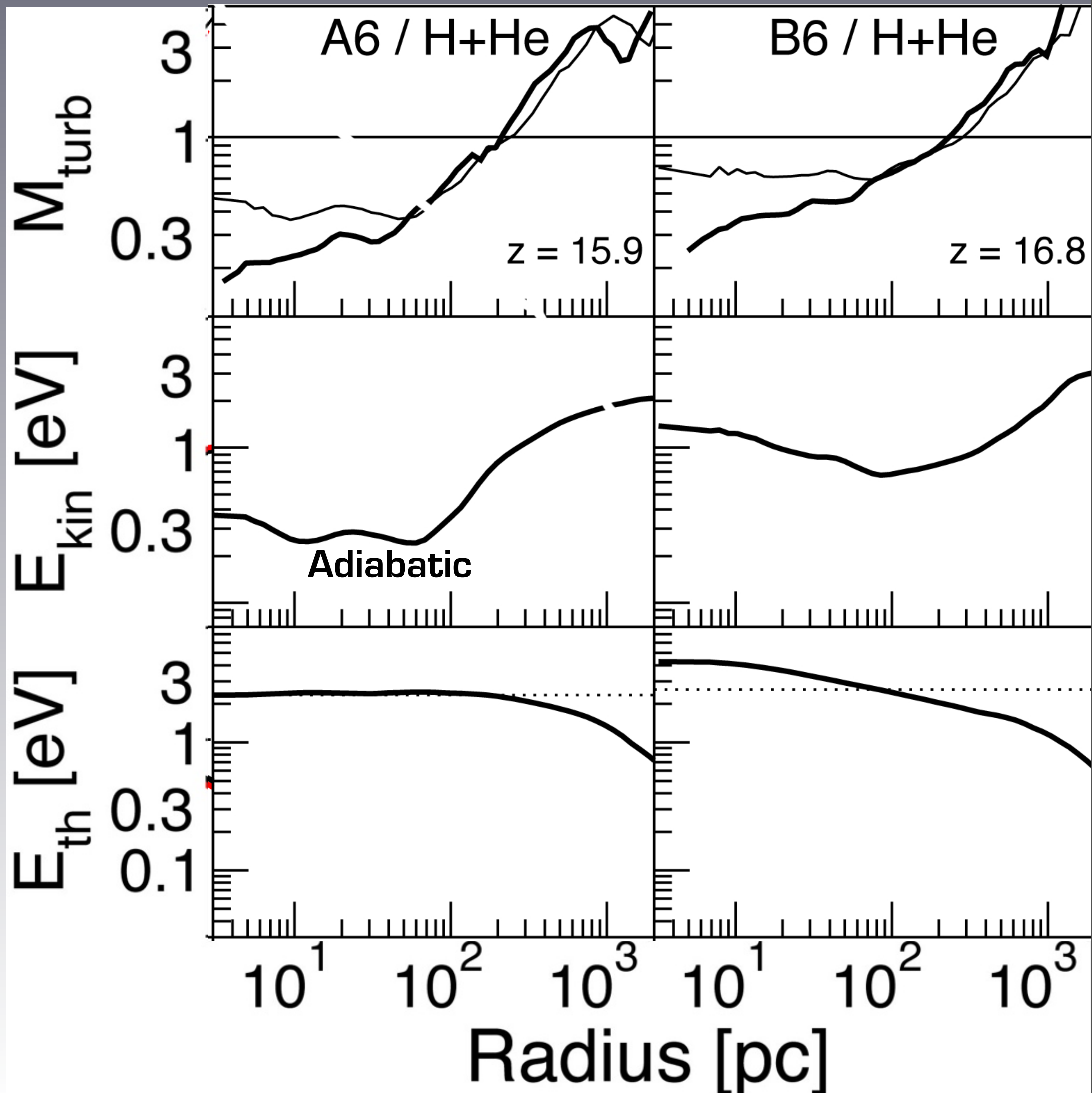
Wise & Abel (2007)

Virial Turbulence

- In cooling halos, virialize through turbulence.
- Kinetic energy increases up to 5 times with cooling.
- Turbulent Mach numbers = 1–2



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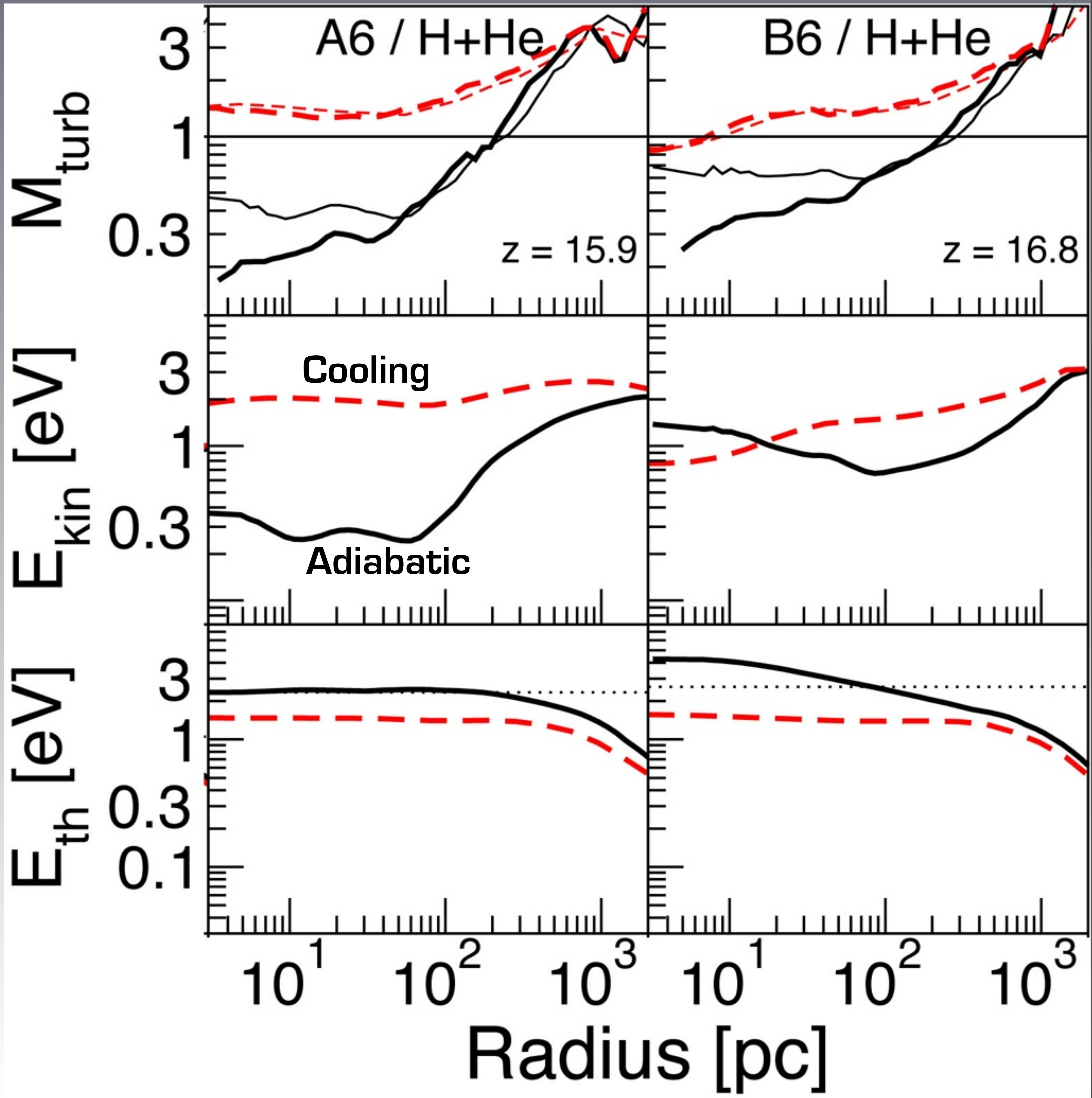
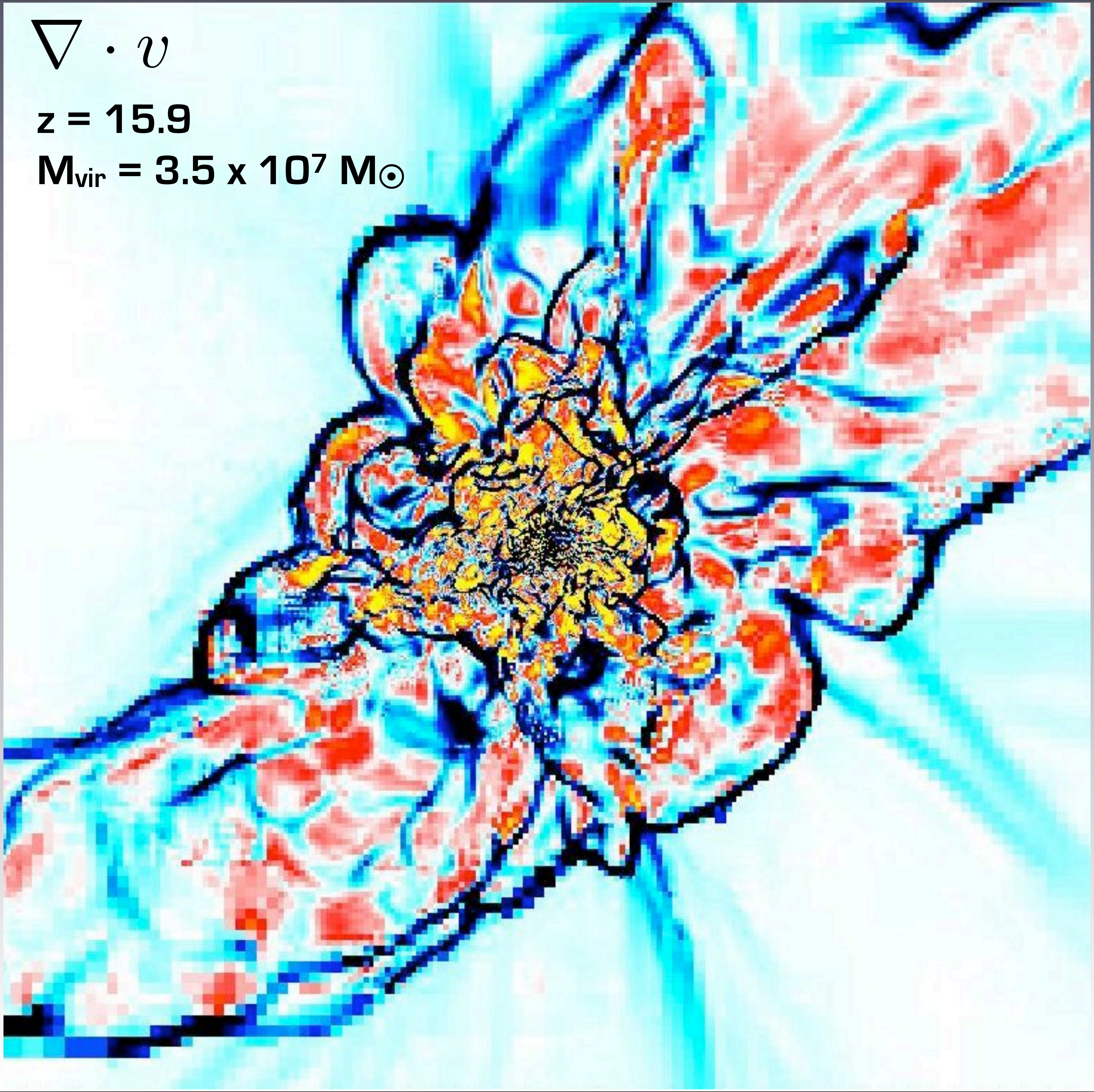
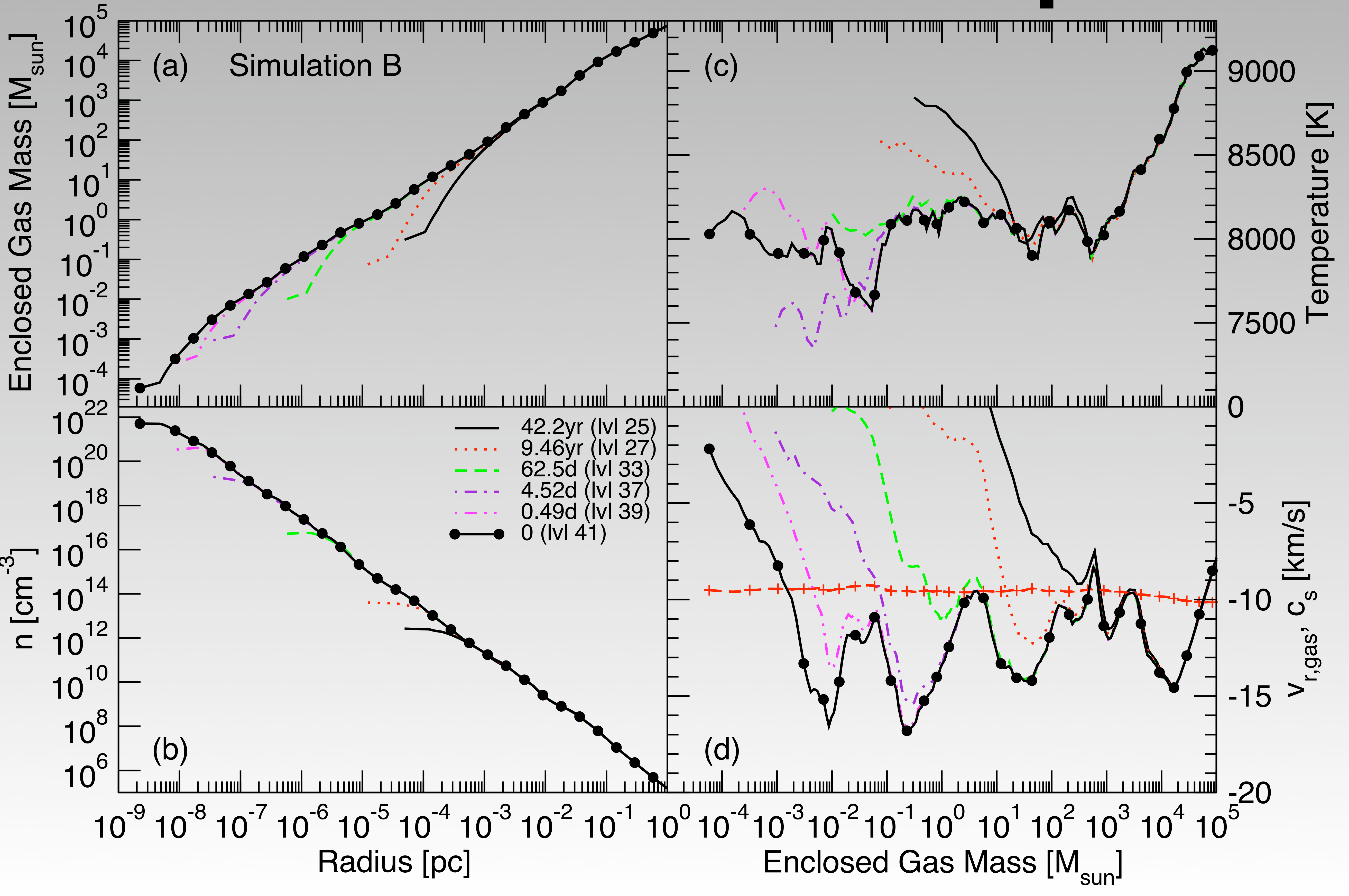



$\nabla \cdot v$
z = 15.9
M_{vir} = 3.5 x 10^7 $M_\odot$

Wise, Turk & Abel (2008)
arXiv:0710.1678

Gravitational Collapse



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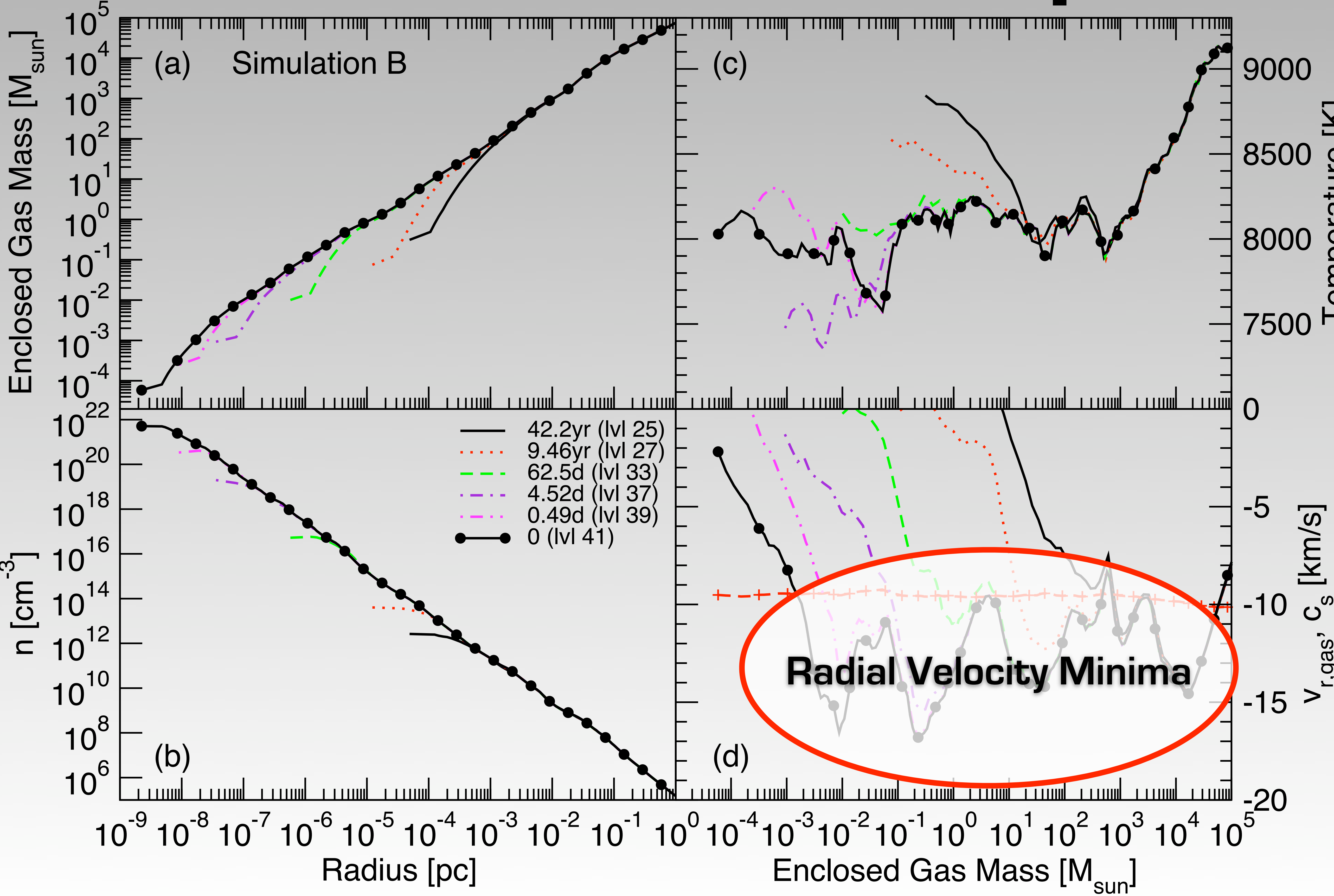

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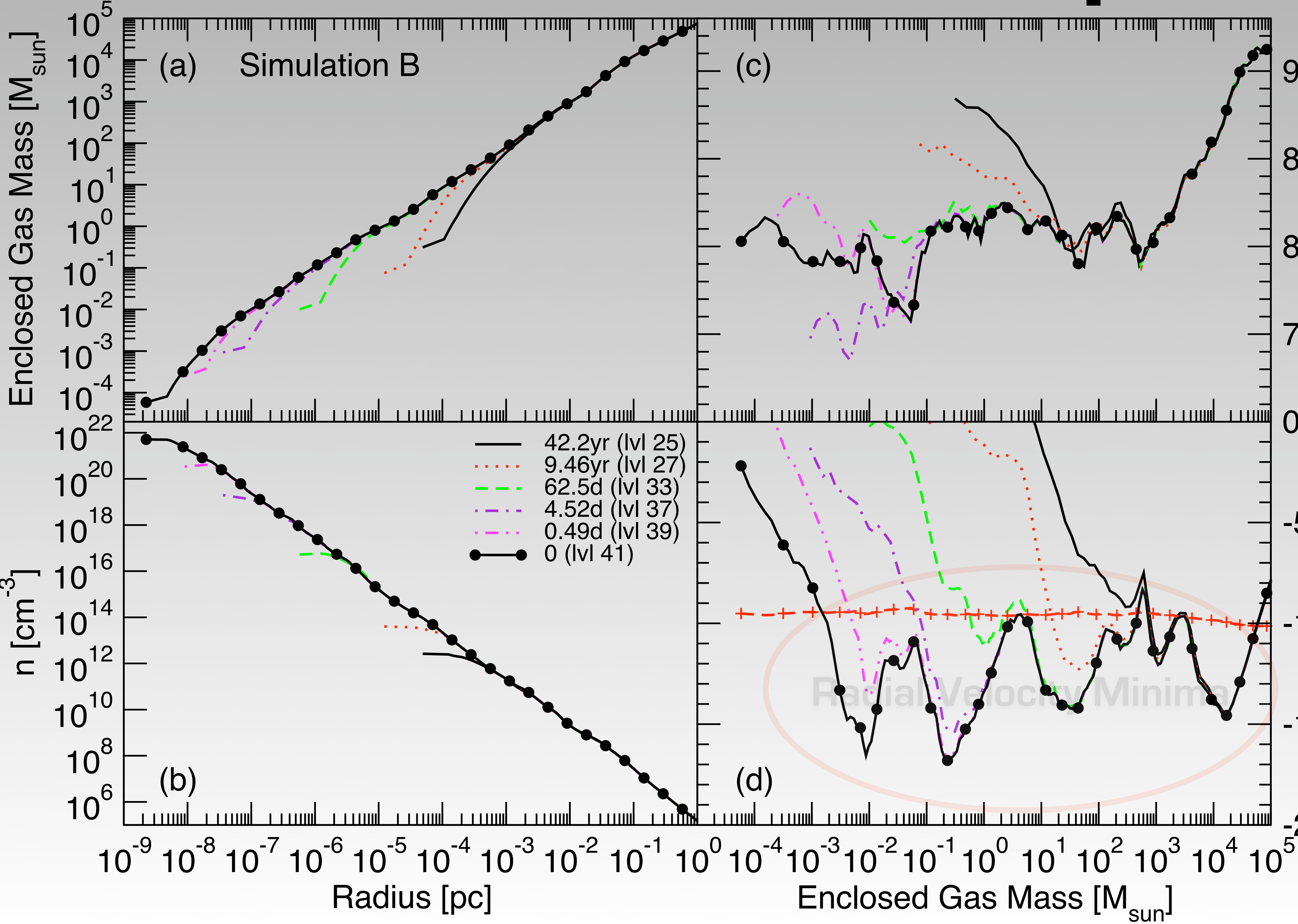

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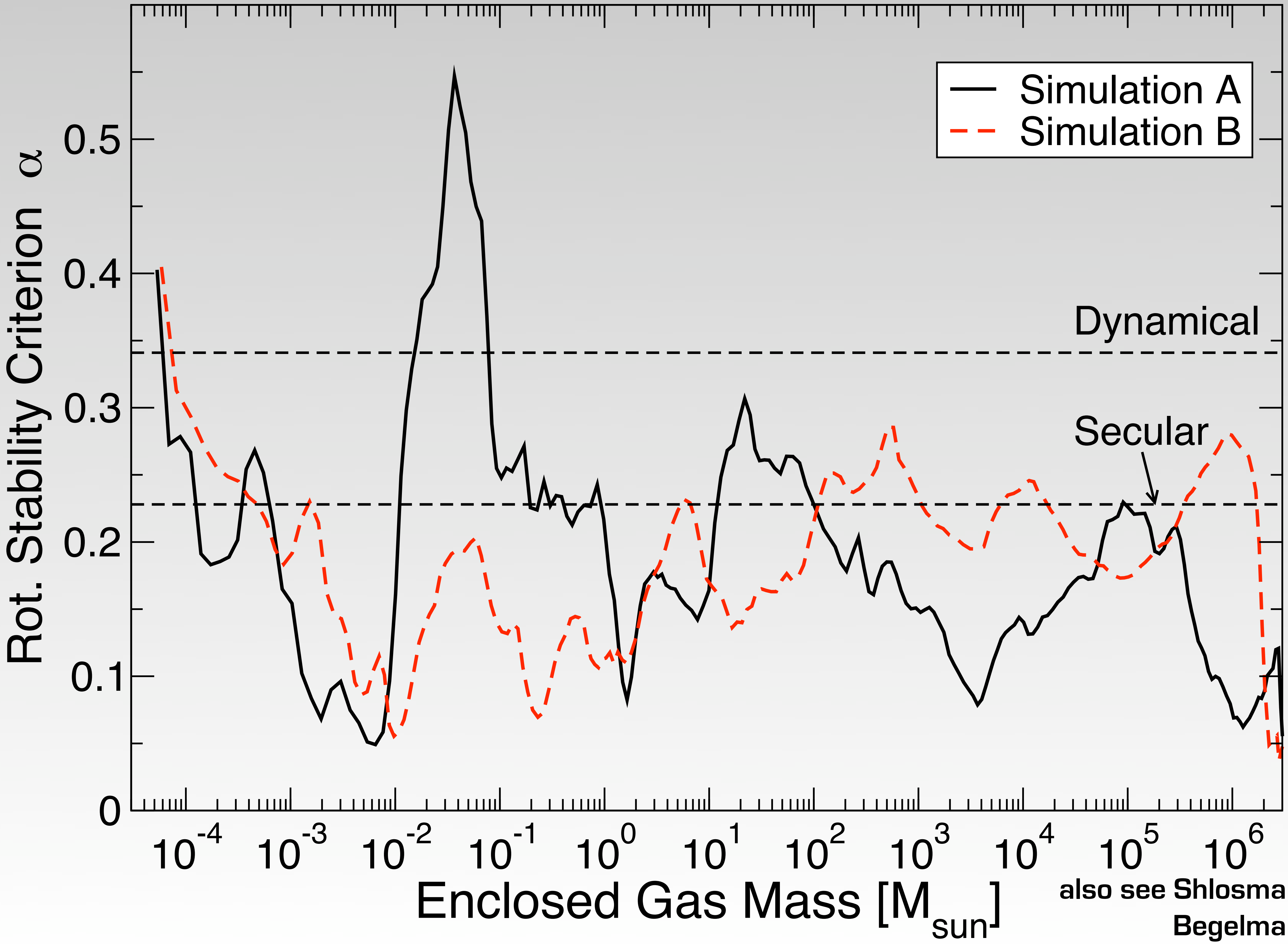
Gravitational Collapse

Rotational bar instabilities



also see Shlosman et al. (1989)
Begelman et al. (2006)

Wise, Turk & Abel (2008)
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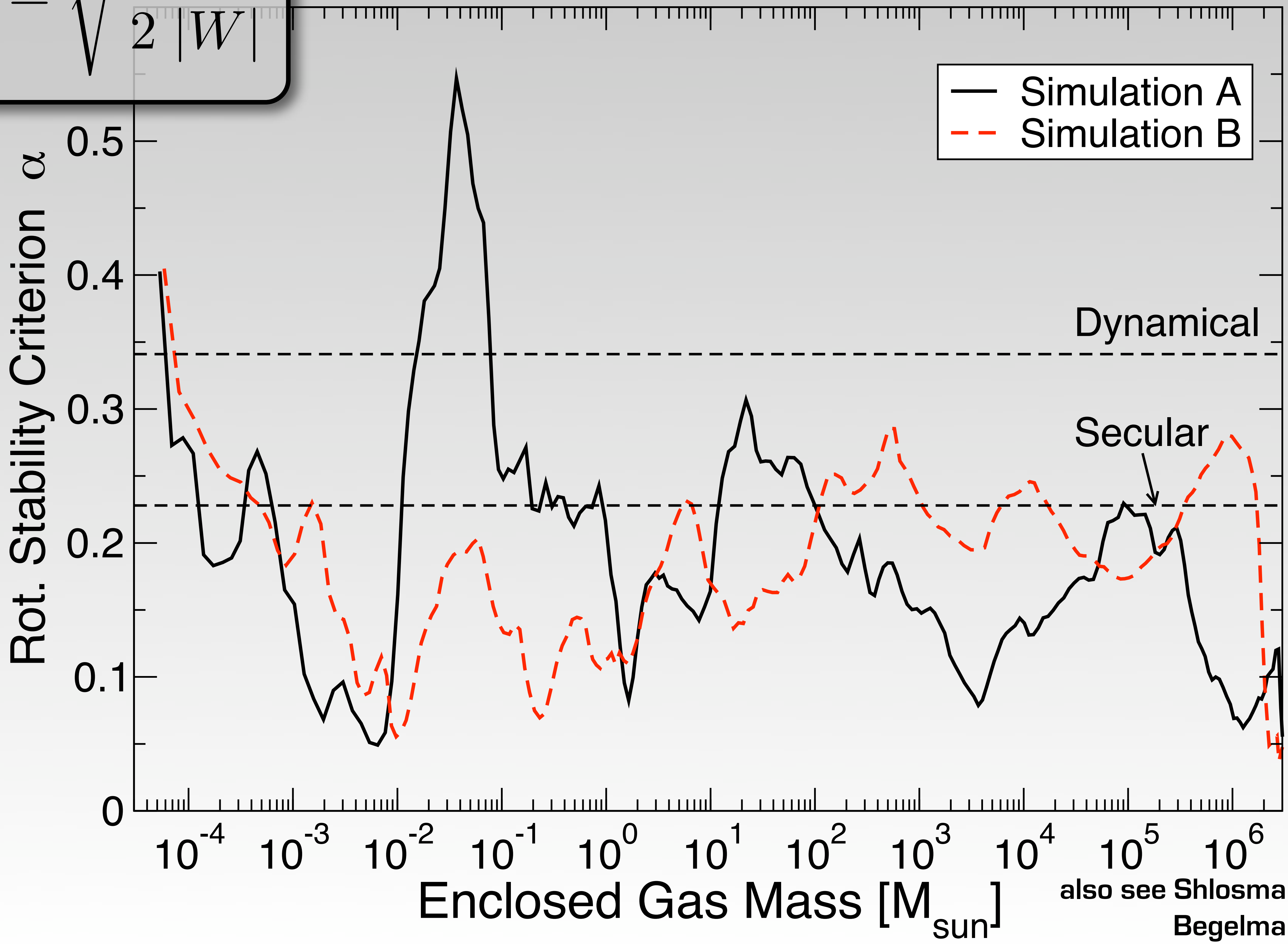
Gravitational Collapse

Rotational bar instabilities

$$\alpha = \sqrt{\frac{f}{2}\frac{T}{|W|}}$$



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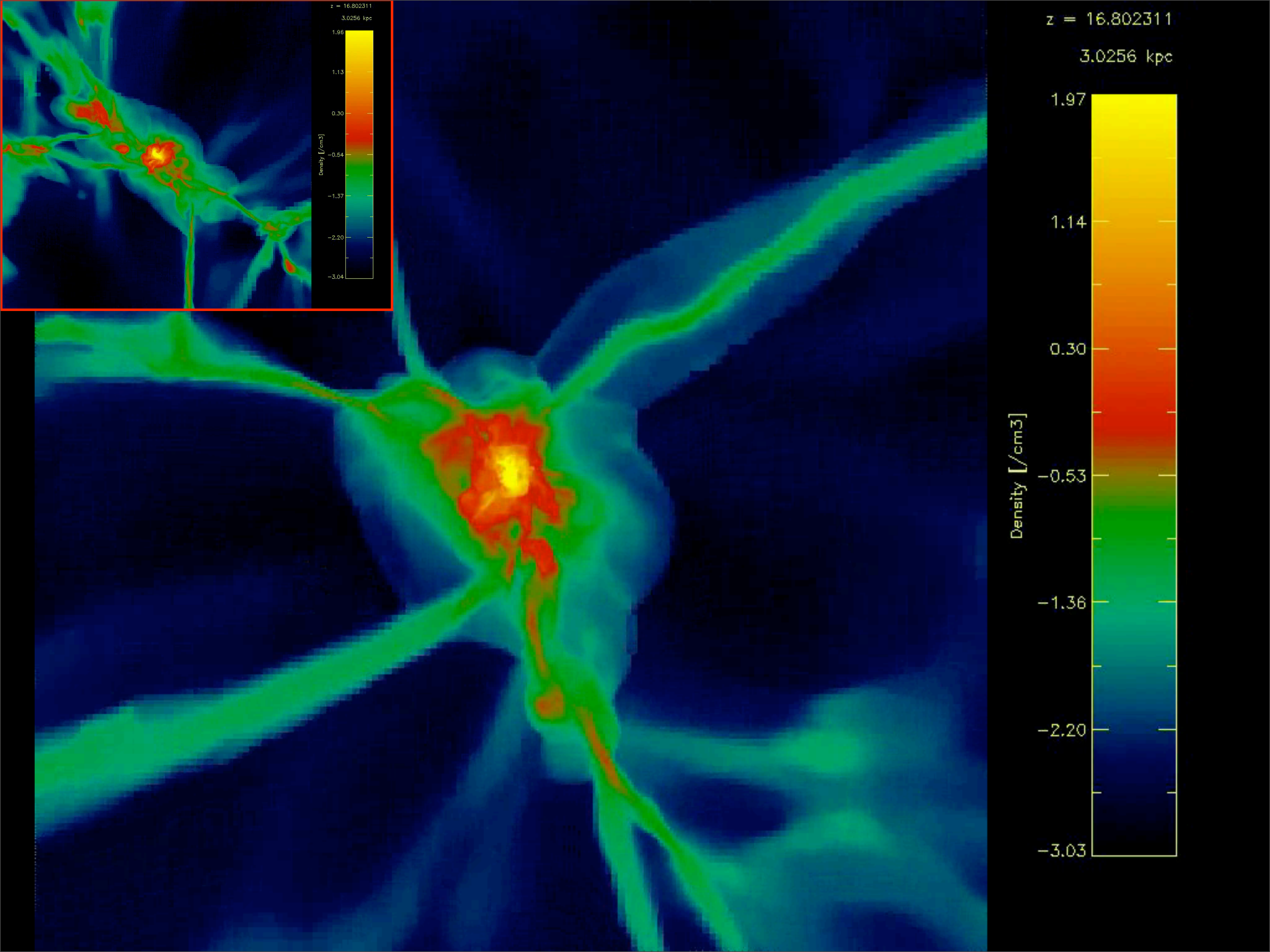
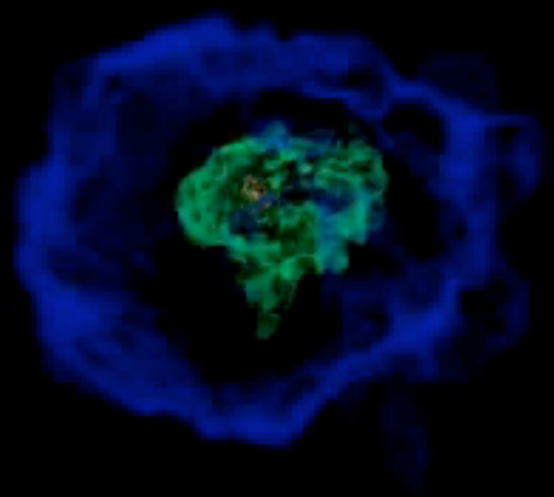
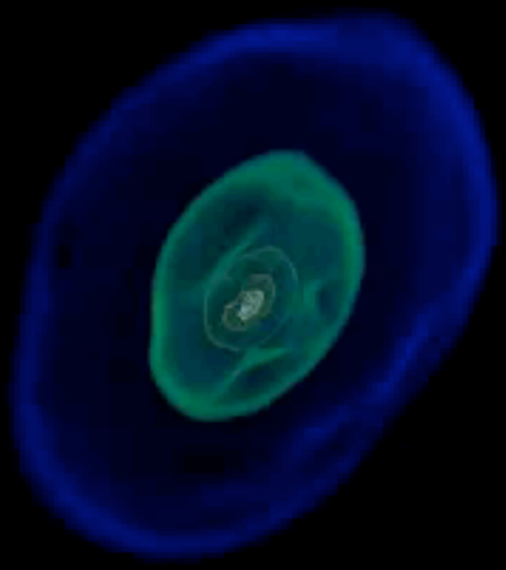


z = 16.802311
3.0256 kpc
1.96
1.13
0.30
−0.54
−1.37
−2.20
−3.04
Density [/cm3]
z = 16.802311
3.0256 kpc
1.97
1.14
0.30
−0.53
−1.36
−2.20
−3.03
Density [/cm3]

Comparison of the two collapses

Starts at 30 proper pc





Simulation A

Recent major merger

Highly disorganized

Rotational instabilities

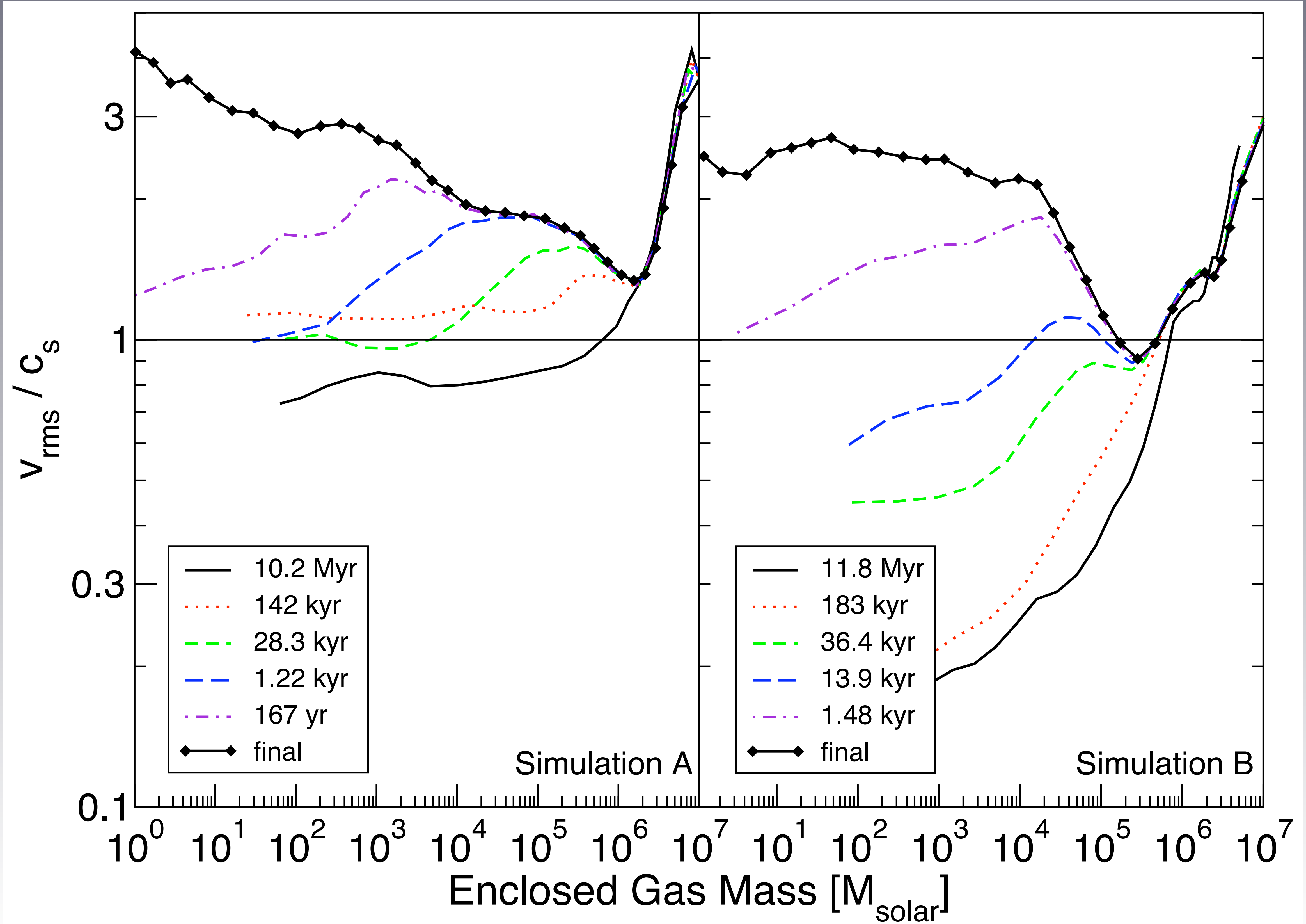
Simulation B

No recent major mergers

Organized rotation 1/3 of the Keplerian velocity

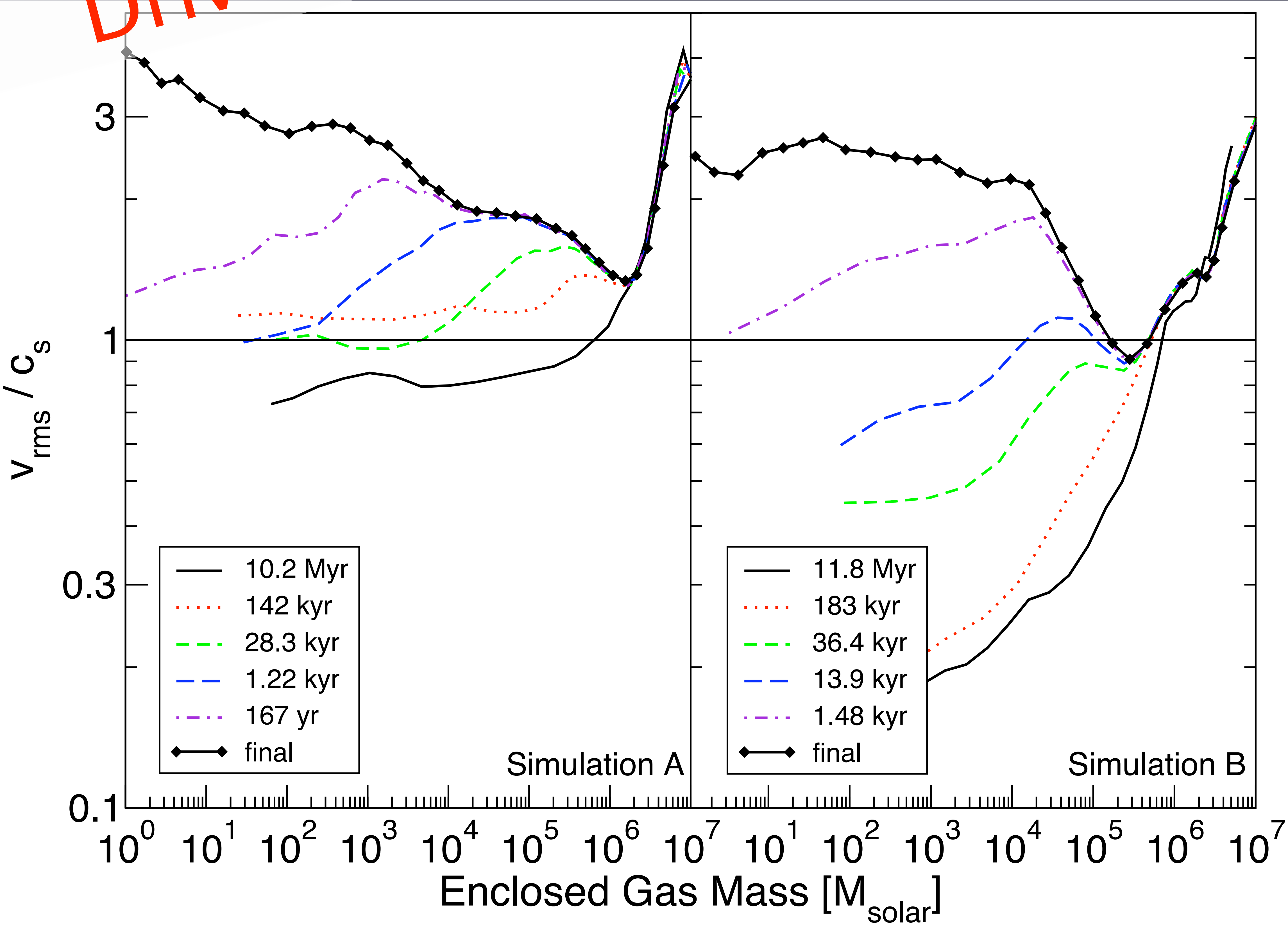
Rotational instabilities

Supersonic Turbulence

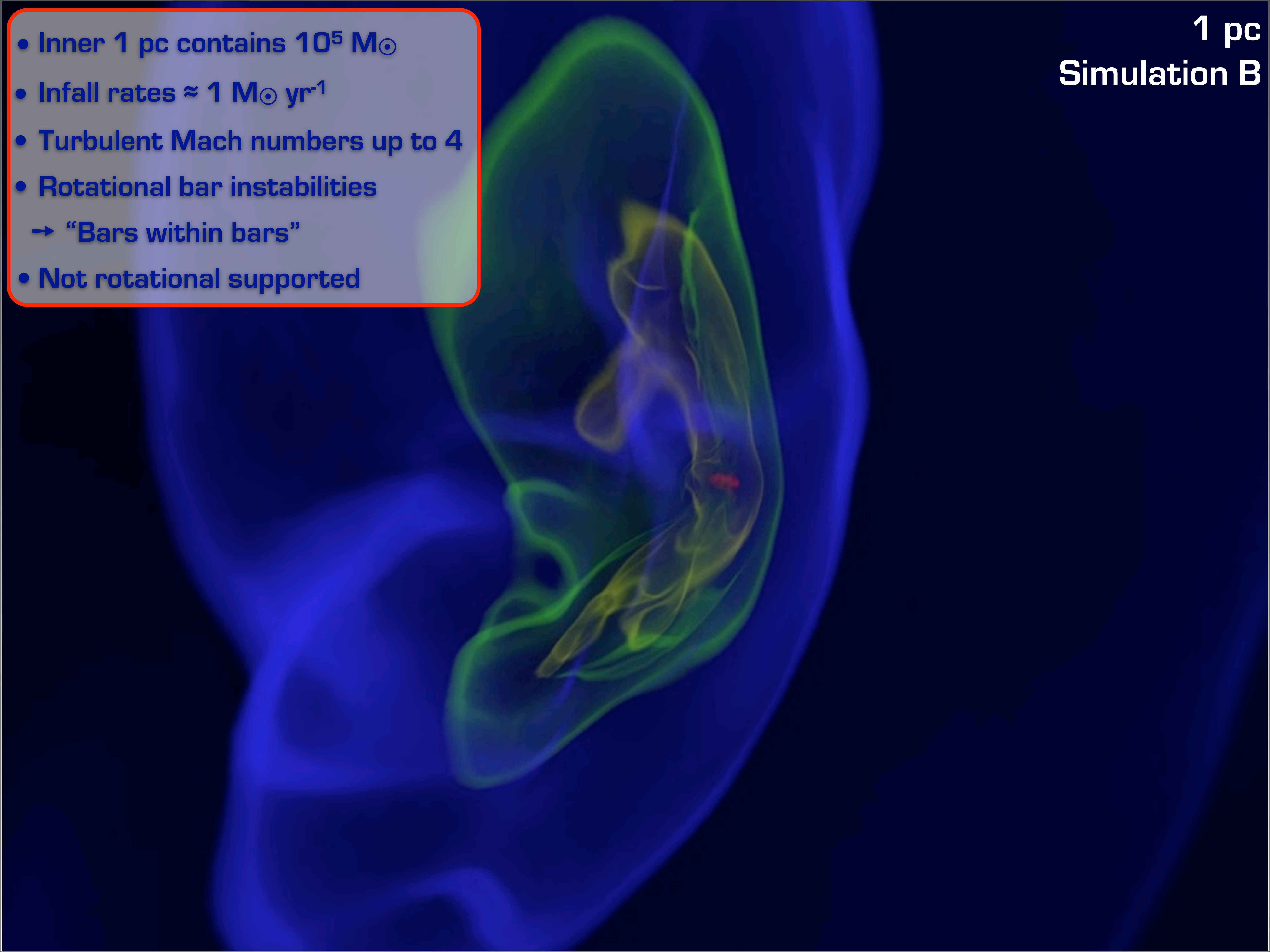


Supersonic Turbulence

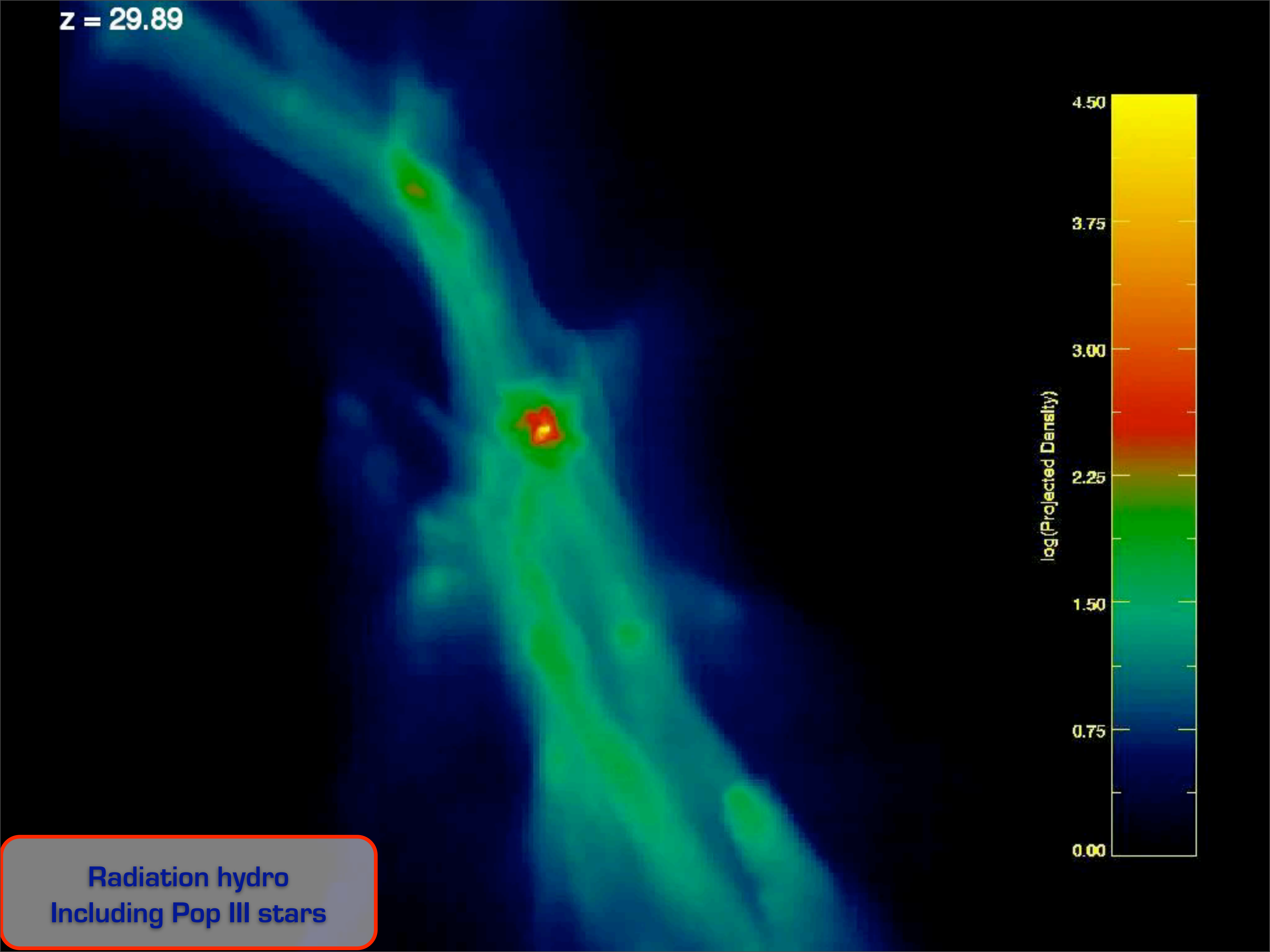
Collapse Driven



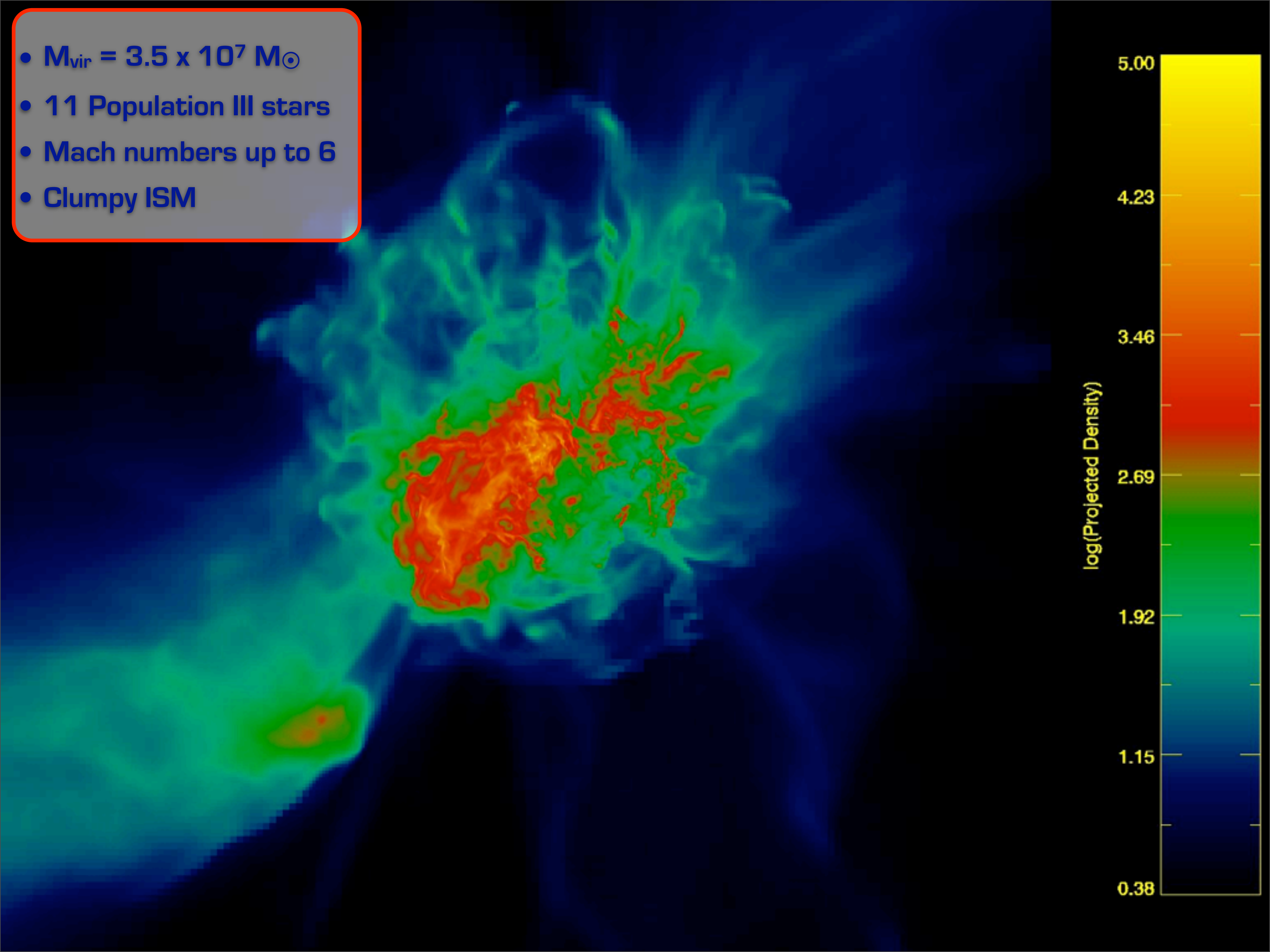
- Inner 1 pc contains 10^5 $M_\odot$
- Infall rates ≈ 1 $M_\odot$ yr^{-1}
- Turbulent Mach numbers up to 4
- Rotational bar instabilities
  → “Bars within bars”
- Not rotational supported



Radiation hydro
Including Pop III stars


z = 29.89
4.50
3.75
3.00
2.25
1.50
0.75
0.00
log(Projected Density)
Radiation hydro
Including Pop III stars

- $M_{vir} = 3.5 \times 10^7 M_\odot$
- 11 Population III stars
- Mach numbers up to 6
- Clumpy ISM



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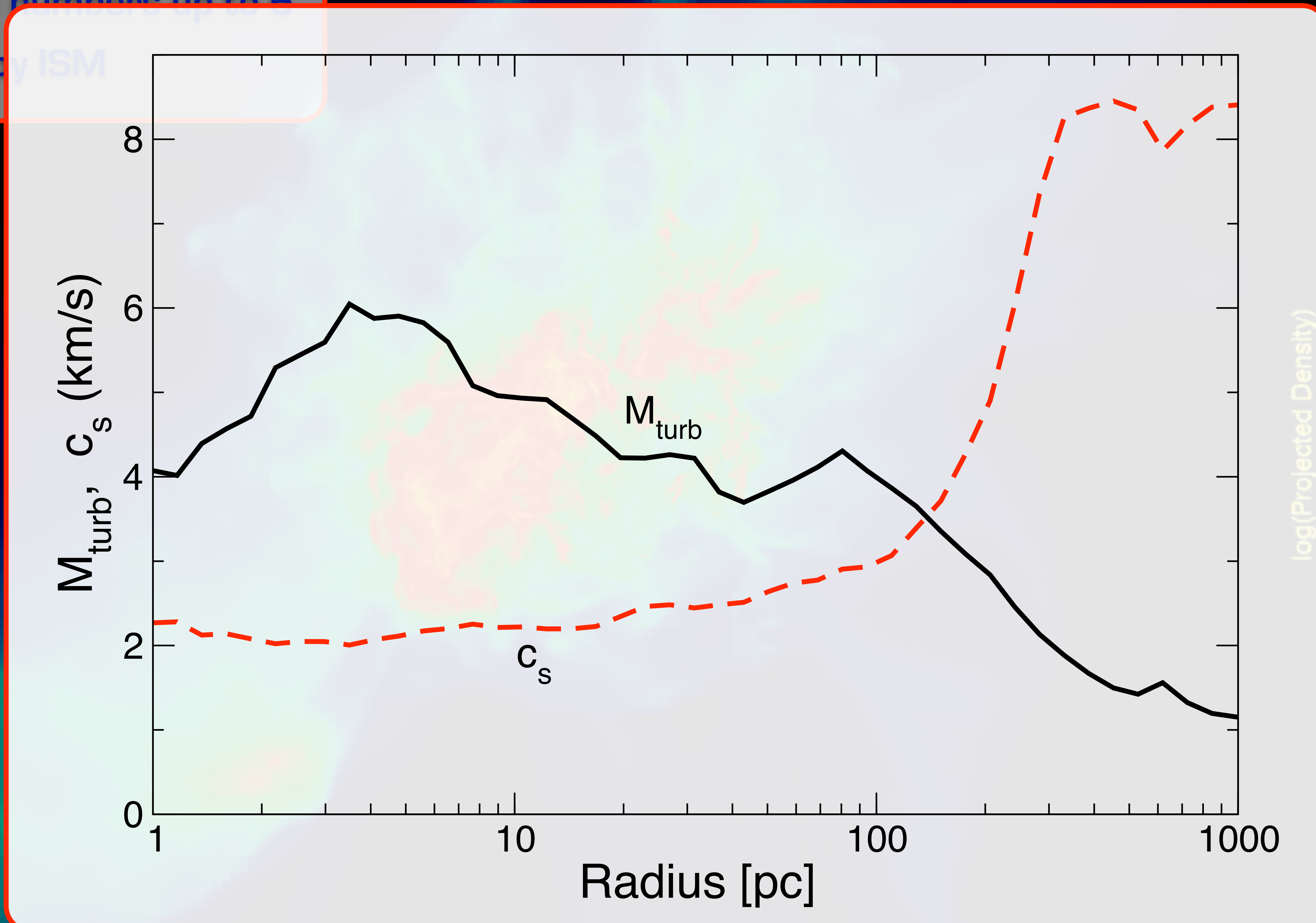

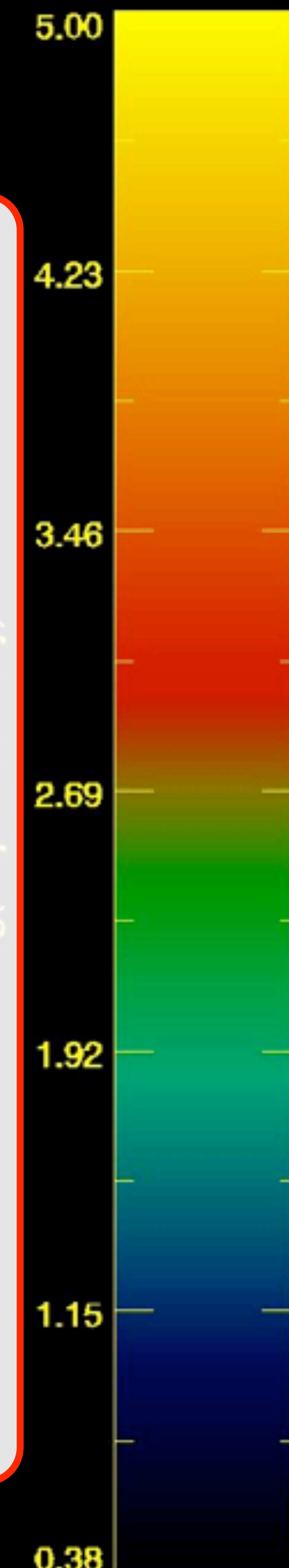

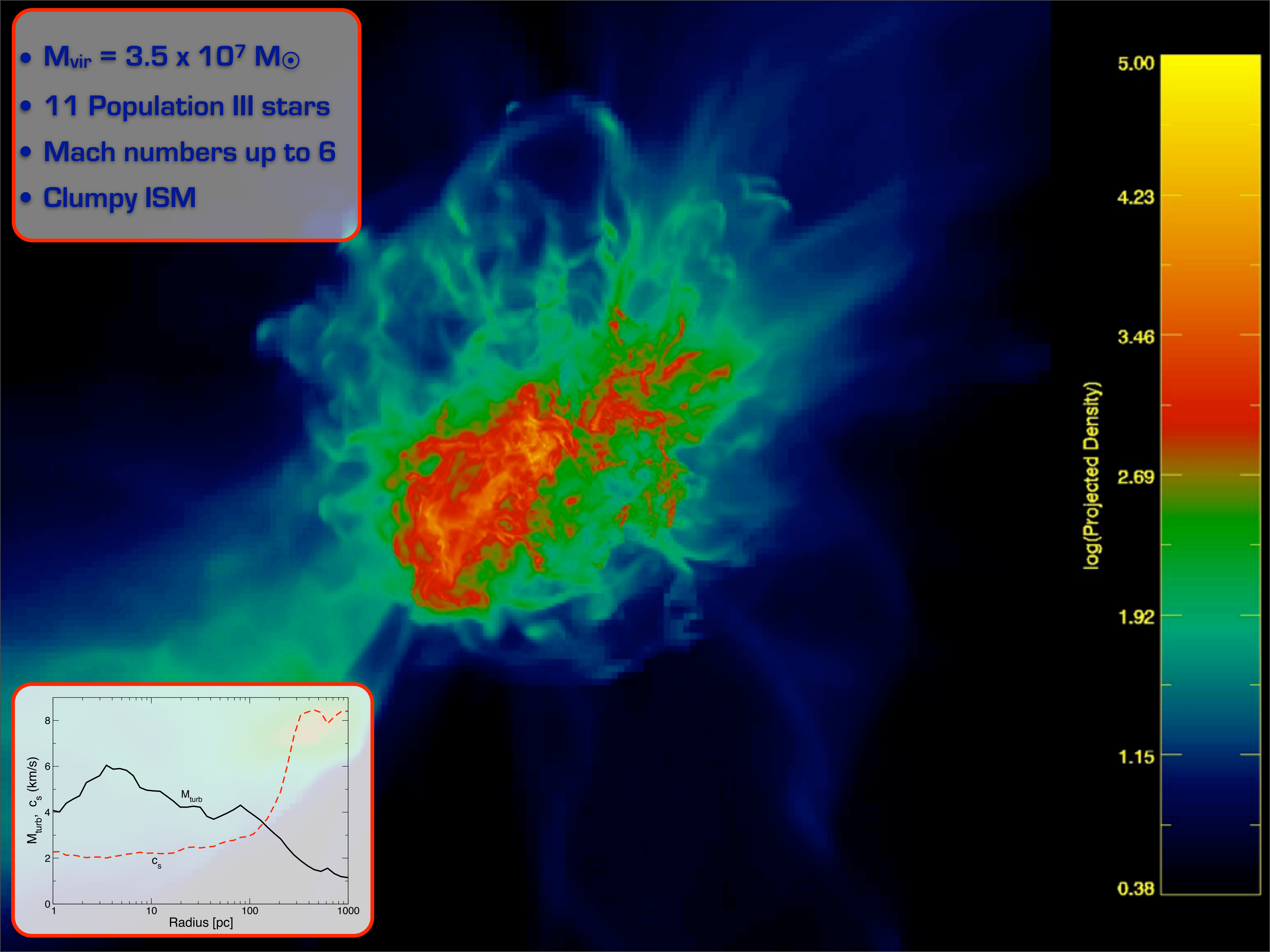

• M_{vir} = 3.5 x 10^7 $M_\odot$
• 11 Population III stars
• Mach numbers up to 6
• Clumpy ISM
log(Projected Density)
5.00
4.23
3.46
2.69
1.92
1.15
0.38
M_{turb}, c_s (km/s)
Radius [pc]
M_{turb}
c_s
0
2
4
6
8
1
10
100
1000

Summary

- Virialization of halos create supersonic turbulence in addition to shock-heating the gas.
- Dense central cores of 10^5 $M_\odot$ with r = 1pc form and further collapse by transporting angular momentum through rotational bar instabilities.
- Supersonic turbulence is driven on timescales shorter than it is dissipated

→ turbulent Mach numbers up to 4

- Stellar feedback and H_2 cooling in more realistic studies result in even greater supersonic turbulence (Mach numbers reaching 6).